ABL flow fields and wake affected flow fields in a wind turbine load perspective

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Wind energy is a multidisciplinary field of activity comprising elements of e.g. fluid mechanics, structural mechanics, material science, statistics, control theory, system identification and power electronics. Most of these disciplines are further required for a rational design of a wind turbine.

Ensuring the structural integrity of integrity of a wind turbine structure basically involves analysis of *fatigue* loading as well as of *ultimate* loading during the turbines target lifetime. These analyses are traditionally based on *aero-elastic* simulations, where the relevant external loading is applied to a dynamic system constituted by the elastic wind turbine [1], [2], [3]. The wording "aero-elastic" indicates a feed-back mechanism between the aerodynamic loading and the elastic response of the structure, which is indeed the case. The design process is elaborate, as it in principle involves all relevant load cases to be investigated, including loads caused by transport and installation of the wind turbine, ice loads causing aerodynamic and mass un-balances, fault conditions, start up and shut down events, normal operation, etc..

In the present context focus is on load patterns associated with *normal operation* of the turbine. In this case the loading may be split into a *deterministic* part (caused by static wind field forces, gravity forces, centrifugal forces) and a *stochastic* part caused by turbulence (and in addition wave loading for offshore sites). This presentation will address basic load generating features of the atmospheric boundary layer (ABL) with particular emphasis on wake affected flows as experienced in wind farms.

The mean wind field and the gravity impact the fatigue loading, whereas these are of secondary importance only when it comes to ultimate loading. The turbulence loading is important for both fatigue and ultimate load prediction. Contrary to the turbulent part of the ABL, characterization and modeling of the *mean flow field* (including possible atmospheric stability effects etc.) is usually straight forward. As for the *turbulence* part, synthetic fields reflecting realistic temporal and spatial variations of the turbulence field in question (i.e. with a priory specified second order statistics) are traditionally generated based either on the concept of an ABL spectral tensor (e.g. Mann [4] that, based on an assumed neutral atmospheric stratification, combines Rapid Distortion Theory, an assumed linear mean wind shear, a model for eddy lifetime and the von Karman spectral tensor [5]) or, alternatively, using the general algorithm of Shinozuka [6] for generation of stochastic fields.

Although the spectral tensor in principle contains the same information as the cross spectra, the tensor formulation leads to considerable simpler and faster simulation algorithms for turbulence simulation than the cross spectra based methods. On the other hand the Shinozuka approach is a more versatile formulation that, contrary to the spectral tensor approach, allow for generation of e.g. inhomogeneous turbulence fields, non-stationary fields and non-Gaussian fields, however, on the cost more detailed input requirements for the cross-spectral properties [7]. Usually, Gaussian statistics is assumed for the stochastic turbulence fields which suffice for simple terrain categories. However, in complex terrain sites the turbulence fields often displays a non-Gaussian behavior which calls for the more general methods for synthetic turbulence generation.

In practice, it is not possible to base estimation of turbulence driven *ultimate loading* on extreme external events extracted from (horrendous long) synthetic turbulence time series. A supplementing approach addressing this problem, in combination with statistical models of most likely gust amplitudes for predefined short term gust types, is the concept of *constraint simulation*. A versatile theory for constraint simulation of

Gaussian turbulence driven gust situations has been developed [8], [9], and statistical models for rational gust amplitude prediction are underway. The theory provides generation of predefined consistent synthetic turbulence fields, consisting of fully 3D multiple correlated stochastic processes, containing one or more extreme events (arbitrarily distributed in space and/or time), with the second order structure functions correctly represented. The spatial extent of these events results directly from the cross correlation properties of the stochastic field in which they are embedded.

Within the framework of the derived formalism, an extreme event is defined in terms of an arbitrary number of constraints, each expressed as a *linear combination* of an arbitrary number of turbulence field velocity components and/or their derivatives. The theory has been implemented in a framework, where the basic stochastic field is generated using the Mann spectral tensor formalism, but can equally well be applied with the Shinozuka approach.

In addition to conventional turbulence loading, caused by undisturbed/ambient ABL turbulence fields as described above, the additional stochastic loading in *wind farms* as caused by *meandering wakes*, possesses a particular challenge. The downstream advection of a wake from the upstream emitting turbine describes a stochastic pattern known as *wake meandering* as illustrated in Figure 1. It appears as an *intermittent phenomenon*, where winds at downwind positions may be undisturbed for part of the time, but interrupted by episodes of intense turbulence and reduced mean velocity as the wake "hits" the observation point. Although different in nature compared to traditional turbulence, the resulting wind field may be considered as a turbulence field with intermittent characteristics, with a significantly modified turbulence *structure* and with increased "apparent" turbulence *intensity*. The notation "apparent" turbulence intensity indicates that the turbulence intensity contains contribution from both traditionally generated turbulence and from the wind speed variation caused by the instantaneous transversal- and vertical movements of the wake "emitted" from the upstream turbine.

Recent research, based on a combination of CFD LES actuator line simulations and analysis of LiDAR based full-scale experiments, has lead to characterization of the large scale dynamics of wake meandering [10], [11] and revealed insight in the character of the self-generated wake turbulence [12], [13], and thereby facilitated approximate numerical simulation of such fields suitable for turbine (fatigue) load and production prediction. The self generated wake turbulence turns out to display significant in-homogeneous field characteristics, with turbulence integral length scales considerable less than the length scale of conventional ABL turbulence and, in addition, with a somewhat stronger coherence decay (consistent with the smaller than ABL turbulence integral length scale!). With a detailed characterization of wake flow fields in hand the way is paved for development techniques for topology optimization of wind farms [14] taking into account production as well as *fatigue* driven degradation of the wind turbine structures.

However, when it comes to ultimate loading associated with wake affected flow fields, rational tools combining the statistics of the ambient undisturbed ABL flows with the statistics of the stochastic wake meandering of the organized flow structure constituted by the wake deficit and the self-generated wake (small-scale) turbulence is still lacking and thus an obvious topic for future research.

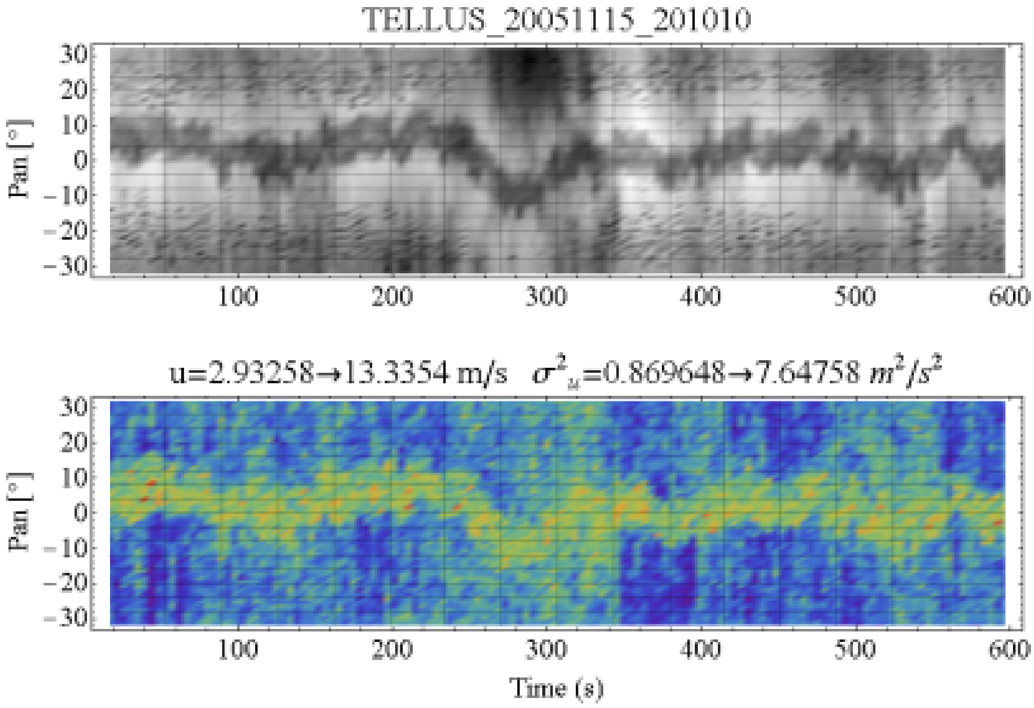

Figure 1: A meandering *wake deficit* and the associated *small-scale wake turbulence* resolved from full-scale LiDAR measurements in a cross section 58m downstream the wake generating rotor. The upper figure shows the position of the wake deficit as function of time (dark colors indicated low wind speed), whereas the lower figure shows the variance fields as function of time (yellow/orange colors indicate high variance).

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